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Biomechanics of Injuries to the Foot and Ankle Joint of Car Drivers and Improvements for an Optimal Car Floor Development

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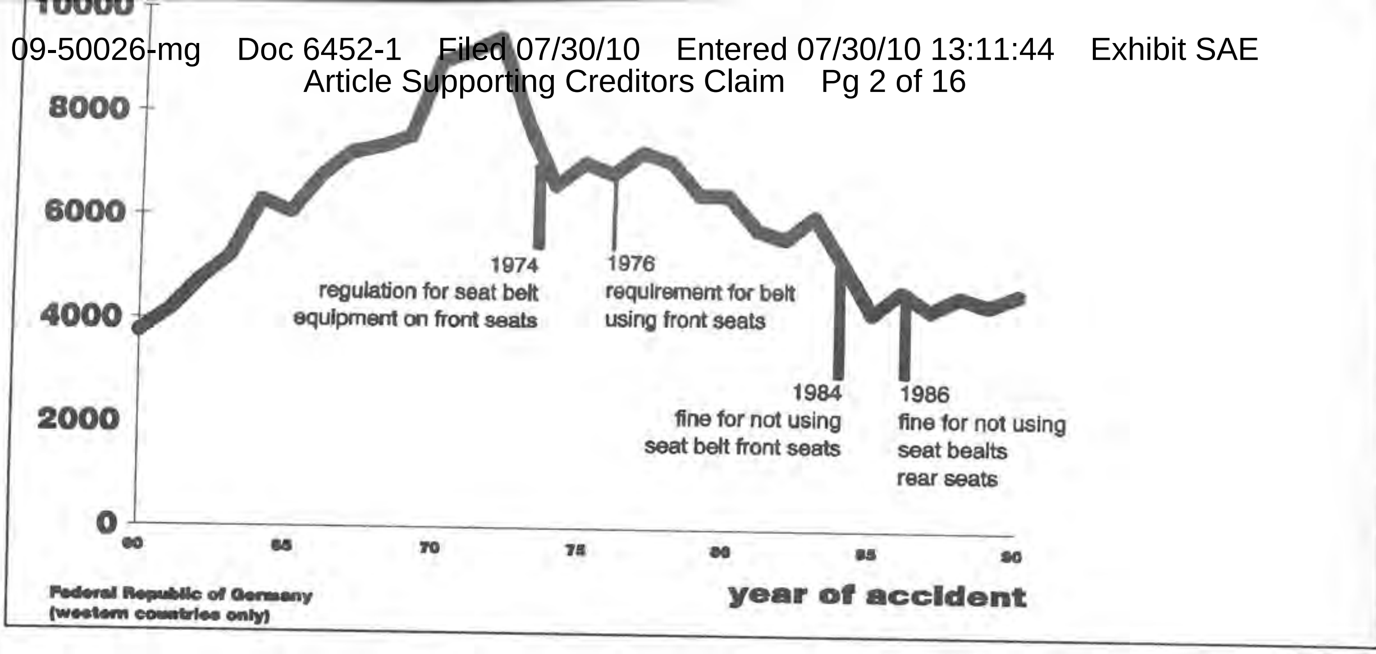
Abstract

In the study 140 belt-protected car drivers with foot fractures, distortions and luxations were analysed and the injury mechanisms in the car interior which are responsible for the occurance of foot fractures were defined. Accident documentations carried out from 1985 to 1990 by the traffic accident research of Hannover are the basis of these investigations.
It was established that foot fractures for car drivers are, to an amount of 1.3%, quite rare. In view of the fact, however, that foot fractures result in a rather high rate of injury consequences in treatment it is shown that the demand for modifications of the vehicle interior is justified. The study demonstrates that two characteristic mechanisms must be regarded seperately: This is on the one hand in direct succession the force mechanism which always results from footroom deformations. On the other hand it is a simple supporting and slip-off mechanism of the feet which may already occur in connection with lesser accident severities and without footroom deformations. In the study vehicle-technique solutions are recommended for the reduction of foot injuries.

1. Introduction

In the development of the car, the car interior has been improved as well. While the cars of the 1960's were predominantly equipped with wooden steering wheels and non-bolstered dash boards, the cars of the 1980's and 1990's have steering wheels covered with foamed rubber and bolstered dashboards, impact absorbing elements on the steering wheels as well as airbag and seat belt. The pronounced improvement of the injury situation of car occupants in traffic accidents may not in the last place be attributed to the safety belt. The Official Accident Statistic of the German Federal Republic shows for the former territory of the republic (fig. 1), beginning at 1971, a constant reduction in the number of fatal car occupants. Especially in frontal collisions, the seat belt proved its high protective quality. It became evident that the injury pattern of car passengers was visibly changed by the seat belt (Otte et al., 1).

Gögler (2) did show in an investigation in 1976 that only 20% of the injured car occupants were protected by safety belts. Predominating as injury sources were the windscreen with 30% and the steering wheel with 40%. At the Surgeons' Congress at Vienna in 1991 Zeidler (3) however pointed out that in earlier years the windscreen and steering wheel could hardly still be regarded as injury sources, but that in the current situation with belt using of over 90 % the number of injuries caused by the footroom had increased. This relative increase of foot injuries was due to the fact that the seat belt reduced the total num-



ber of injuries and some typical injury causing parts, therefore in the situation with belt including foot fractures as well gives a higher imagination of the foot fracture frequent.

It is the objective of this study to carefully analyse the injury situation of the foot and also the biomechanics of foot injuries as well as the injury mechanisms in the footroom of cars. This can be carried out with a detailed accident analysis, from which beside vehicle deformations and injuries, divided by type, localisation and severity, movement trajectories of occupants in the kinematic and collision phases could be gained.

2. Method

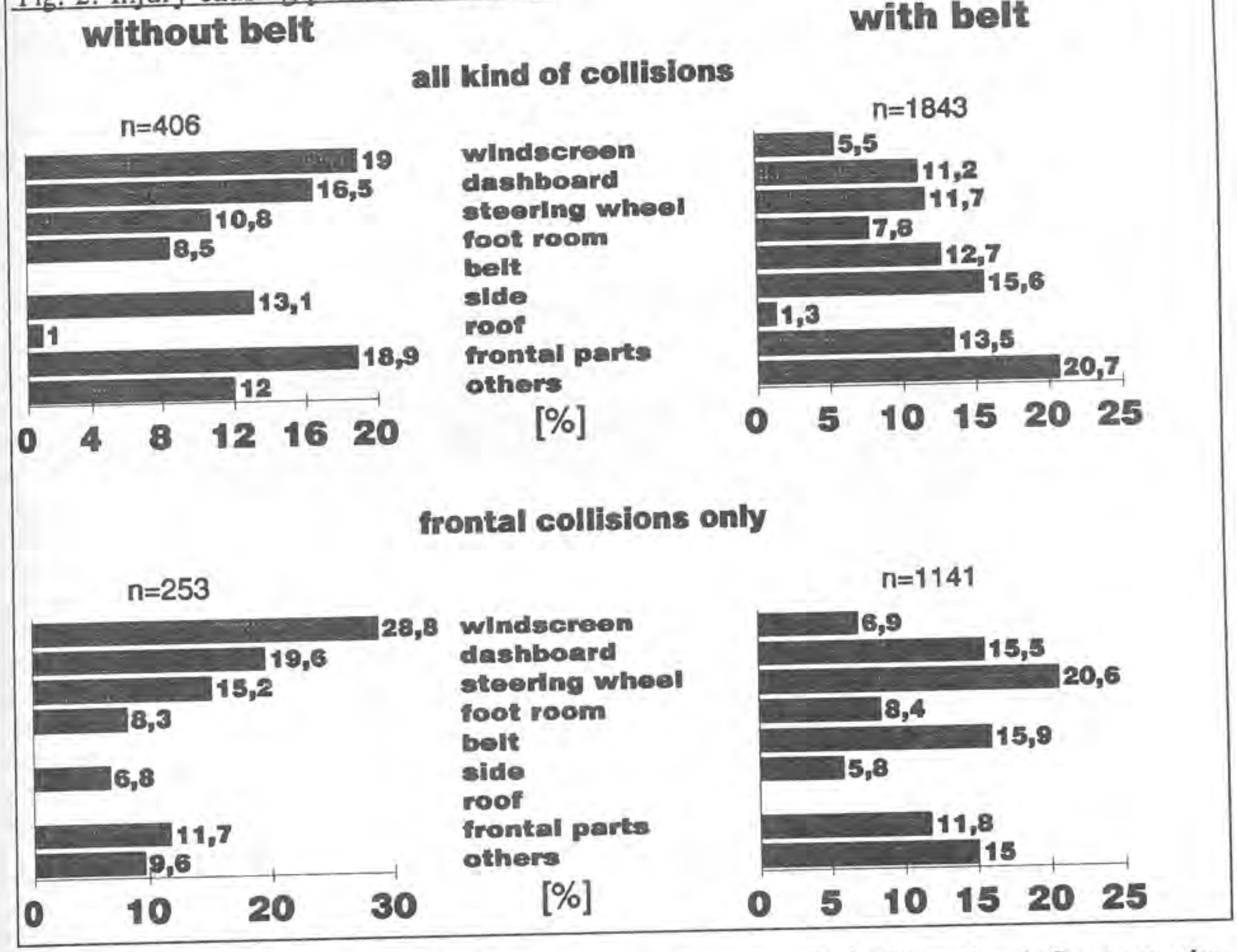
In order to obtain statistically representative results, a continuous accident research, including a statistic spot-check procedure is needed. These demands could be accomplished by accident documentations of the Traffic Accident Research Unit Hannover, which have been carried out continuously since 1985 with a defined spot-check procedure at the site of the accident by a science research team (Dilling, 4).

The team which consists of technicians and medical doctors, approaches in the city and country district of Hannover the site of accidents, immediately after the accident event. Accident traces are registered with a photogrammetric measuring camera. True-to- scale drawings are constructed. This procedure is the basis of an extensive accident reconstruction for the definition of vehicle and occupant kinematics. Medical registrations of the injuries are made, divided into type, localisation and severity, and classified in accordance with AIS (American Association of Automotive Medicine - 5).

3. Injury causes for belted and non belted car drivers

Comparing all single injuries of belt-protected car drivers with those without belt (fig. 2), it becomes evident that without belt 19% of all inju-

Fig. 2: Injury causing parts of car drivers



ries are induced by the region of the windscreen. With belt usage, they are with 5.5% much more rare. With belt usage, the dashboard can also be regarded as injury cause in only 11.2%. Without belt usage 16.5% were caused by an dashboard impact. For the steering wheel, however, the frequency distribution of all injuries to car users with 11.7 and 10.8% respectively shows hardly any difference between belt and non belt usage. With belt usage 7.8% of the injuries, and without 8.5% were attributed to the footroom.

This reveals in the statistic analysis of todays accident situation an insignificantly higher proportion of foot injuries without belt usage. With regard to the frontal impact, the restricted analysis of the accident situation shows with and without belt usage the same proportion of 8.3% of injuries attributed to the footroom. This demonstrates that the use of the safety belt does not, or only insignificantly influences the injury situation of the foot, but that external accident circumstances like deformation and energy transmission play a part to an increased extent.

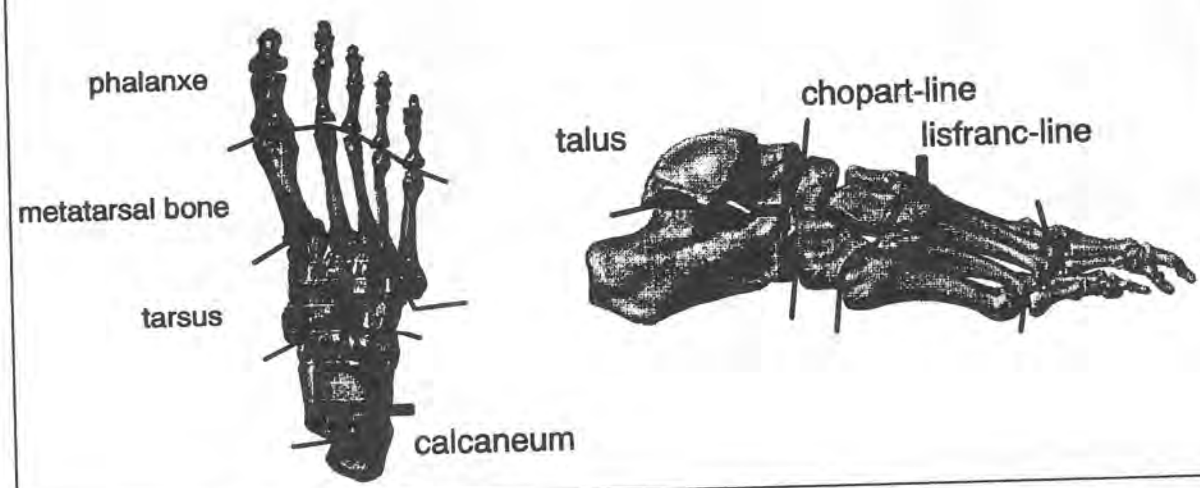
4. Foot Injuries of belted Car Drivers

4.1 Case basis

Accidents of the years 1985 to 1990 were evaluated. These are a case collective established from spot check procedures. The evaluation was carried out as statistically weighting and can be regarded as representative.
140 belt-protected car drivers suffered foot fractures, distortions and luxations. Not included were patients with exclusively soft tissue injuries to the foot region. Each single case was subjected to an in-depth analysis. The injuries are described separately in detail and divided

Fig. 3:

regions of the skeletal foot



into 8 anatomic regions for representation within the framework of this evaluation (fig. 3):

> phalanx, metatarsale, Lis-Franc-joint, tarsus, chopart-joint, talus, calcaneus, ankle joint.

For the definition of injury mechanisms, exclusively car drivers with belt protection were observed, in order to minimize the number of influental factors regarding the resulting injury sequences. Within the framework of the analysis in addition the representative proportion of certain injury patterns for the total collective of all belt-protected drivers n = 5880 was included for demonstration purposes.

4.2 Patterns of foot injuries

The proportion of foot fractures for car drivers can with 1.3% not be regarded as very high, but it is however higher than for co-drivers with 0.7% and for rear-seat passengers with 0.8%. A portion of 36.1% of all foot fractures concerned the region of metatarsale and 37.1% the ankle joint (table 1) . Toe fractures are with 13.0% relatively frequent too, which shows that the medial foot region as well as the ankle-joint are especially exposed to injuries.

Table 1: Region of foot fractures

	n	%			n	%	
phalanx (toe)			**13,0%**	**lisFranc's joint**			**0,0%**
ligamental rupture	1	0,93					
luxation fract. toe joint	2	1,85		**tarsus**			**7,4%**
fracture toe V	4	3,70		cuboideum lig.rupture	2	0,85	
fracture toe I	2	1,85		cuboideum fracture	1	0,93	
fracture toe II	2	1,85		cuneiforme lig.rupture	2	1,85	
fracture toe III	2	1,85		naviculare fracture	1	0,93	
fracture toe IV	1	0,93					
				chopart joint			**0,0%**
metatarsal bone (middle foot)							
basefracture I	1	0,93	**36,1%**	**talus (ancle bone)**			**2,8%**
basefracture III	2	1,85		ligament rupture	1	0,93	
basefracture IV	1	0,93		trochlea fracture	1	0,93	
basefracture V	2	0,85		neck of talus	1	0,93	
subcap. fracture II	2	1,85					
subcap. fracture III	6	5,56		**calcaneum**			**5,6%**
subcap. fracture IV	6	5,56		calcaneumfracture	6	5,56	
subcap. fracture V	5	4,63					
supr.bas.fract. III	2	1,85		**ankle joint**			**37,1%**
supr.bas.fract. IV	1	0,93		distortion	9	8,33	
supr.bas.fract. V	1	0,93		inner maleolus fract.	11	10,19	
capitulumfract. II	1	0,93		UAJ isolated ligament	1	0,93	
capitulumfract. III	3	2,78		UAJ luxation fracture	16	14,81	
capitulumfract. IV	4	3,70		UAJ debris fracture	1	0,93	
capitulumfract. V	2	1,85		Weber-fracture	2	1,85	
total	**108**	**100,00**					

The left foot is with 52.0% only insignificantly more frequently fractured than the right one. Fractures of both feet are established in only 6.8%.

Regarding the toes, it is shown that the base of the 5th limb is especially frequently fractured, while all other toes are not as often and relatively equally involved. In the metatarsale region the centre bones II to IV are involved more frequently and often marked as sucapitale or capitulum fracture respectively.
Fractures of the tarsus are observed in 7.4%.
Fractures in the region of the Lisfranc joint as well as the chopart joint were not observed in connection with belt usage.

On the ankle joint, fractures of the inner malledus are often established, as well as distortions, and especially frequently bimalleore luxation fractures. The latter represent 14.8% of all foot fractures.

Combination fractures, i.e. fractures of the foot in combination with the tibia, so-called "Weber-fractures", are at approximately 2% very rare.

4.3 Accident conditions for foot injuries

Two-thirds of all foot fractures occurred in a frontal impact, one-third in lateral collisions, but none in a rear impact (table 2). It was established that foot fractures in lateral collisions occurred in impact directions from left almost twice as often as from right.

Tab. 2:

seat belted car drivers	total	collision situation frontal	side left	side right
total (n = 108)	100.0%	65.7%	21.3%	13.0%
localisation of foot fracture				
phalanx	13.0%	16.9%	4.3%	7.1%
metatarsal bone	36.1%	39.4%	17.4%	50.0%
tarsus	5.6%	4.2%	4.3%	14.3%
talus	2.8%	2.8%	-	7.1%
calcaneum	5.6%	5.6%	8.7%	-
ankle joint	37.0%	31.0%	65.2%	21.4%

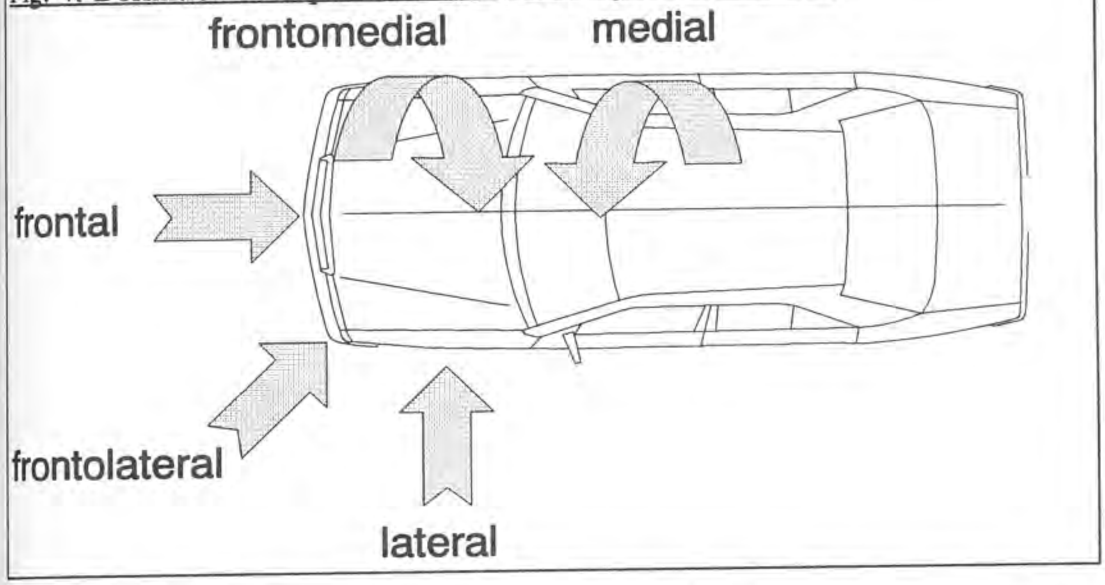
Fractures of the metatarsale are in impacts from left with 17.4% quite rare. The ankle-joint however is in this impact situation with 65.2% especially frequently involved. In the far more frequent frontal collisions the metatarsale with 39.4% and the ankle-joint with 31.0% are most frequently involved. This shows that in the longitudal axis of the vehicle the medial and the fore foot is especially exposed, i.e. the feet positioned on the impact side experience a bending effect. In an impact from right, however, the ankle-joint is not involved that often, but the middle foot including the tarsus region much more frequenty.

This shows that for the occurrance of foot fractures evidently the footroom deformation of the vehicle must be observed. Table 3 demonstrates that three quarters of all foot fractures were connected with a footroom deformation (74.1%).

Tab. 3:

	total	localisation of foot fracture phalanx	metatarsal bone	talus	tarsus	calcaneum	ankle joint
total	102	14	39	3	4	6	40
interior deformation of leg room	74.1%	92.9%	71.8%	100.0%	66.7%	100.0%	65.0%
frontal	41.2%	76.9%	21.4%	33.3%	-	33.3%	53.8%
lateral	8.7%	-	10.7%	33.3%	25.0%	-	7.7%
fronto-lateral	38.7%	23.1%	42.9%	33.3%	50.0%	66.7%	34.6%
fronto-medial	6.2%	-	14.3%	-	-	-	3.8%
medial	5.0%	-	10.7%	-	25.0%	-	-

Fig. 4: Definition of impact load to the foot region of the driver



In almost each case of phalanx, talus and calcaneus fractures a footroom deformation was involved, but not so often in the case of metatarsale fractures (71.8%), and even less frequently in the case of tarsus (66,7%) and ankle-joint fractures (65%).

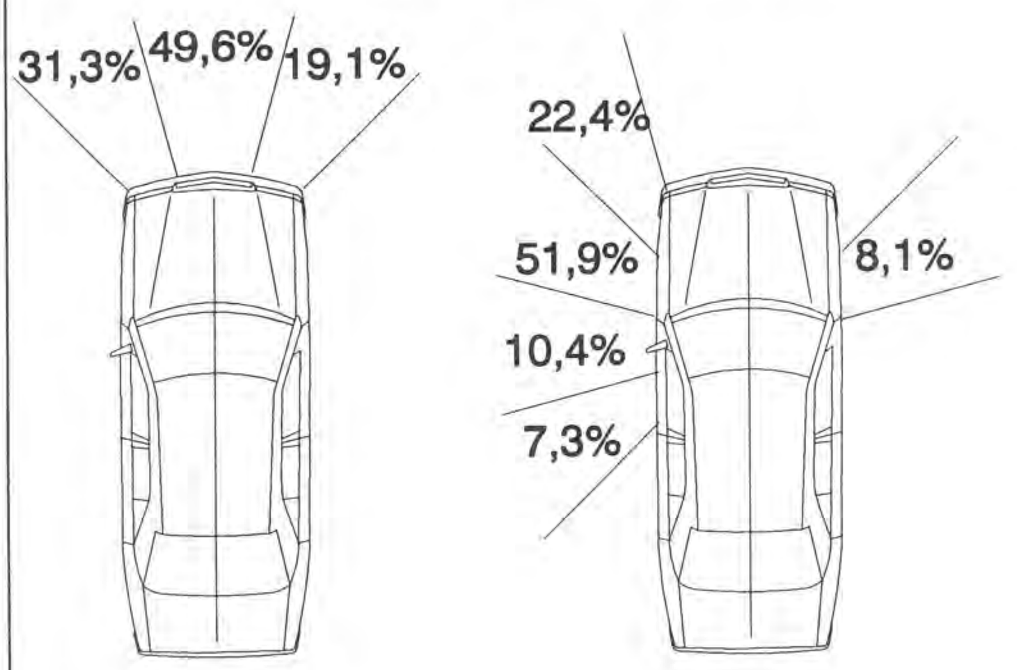
The deformation of the footroom (fig. 4) was predominantly from the front direction (43.4%) or was the result of an oblique frontal impact (38.2% fronto-lateral, 6% fronto-medial).

Within the framework of the accident reconstruction, in each case the impact impulse angle on the vehicle could be defined. It is shown in figure 5 that foot fractures for car drivers with belt too were induced in connection with footroom deformations if in frontal collisions the impact-impulse angle occurred in the region between 11 and 1 o'clock, ie. up to 45 degrees from the left and 45 degrees from right and in lateral collisions between 8 and 11 o'clock. However, especially frequently at 10 o'clock slightly oblique from the front (51.9%). In impacts from right this occurred exclusively in the region between 1 and 2 o'clock.

While phalanx fractures predominate under circumstances of frontal impact directions, the talus, calcaneum and metatarsale are often fractured in a slightly oblique frontal impact direction. For tarsus fractures more lateral impacts could be observed (tab. 3).

Fig. 5:

Impulse direction with leg room deformation and footfractures

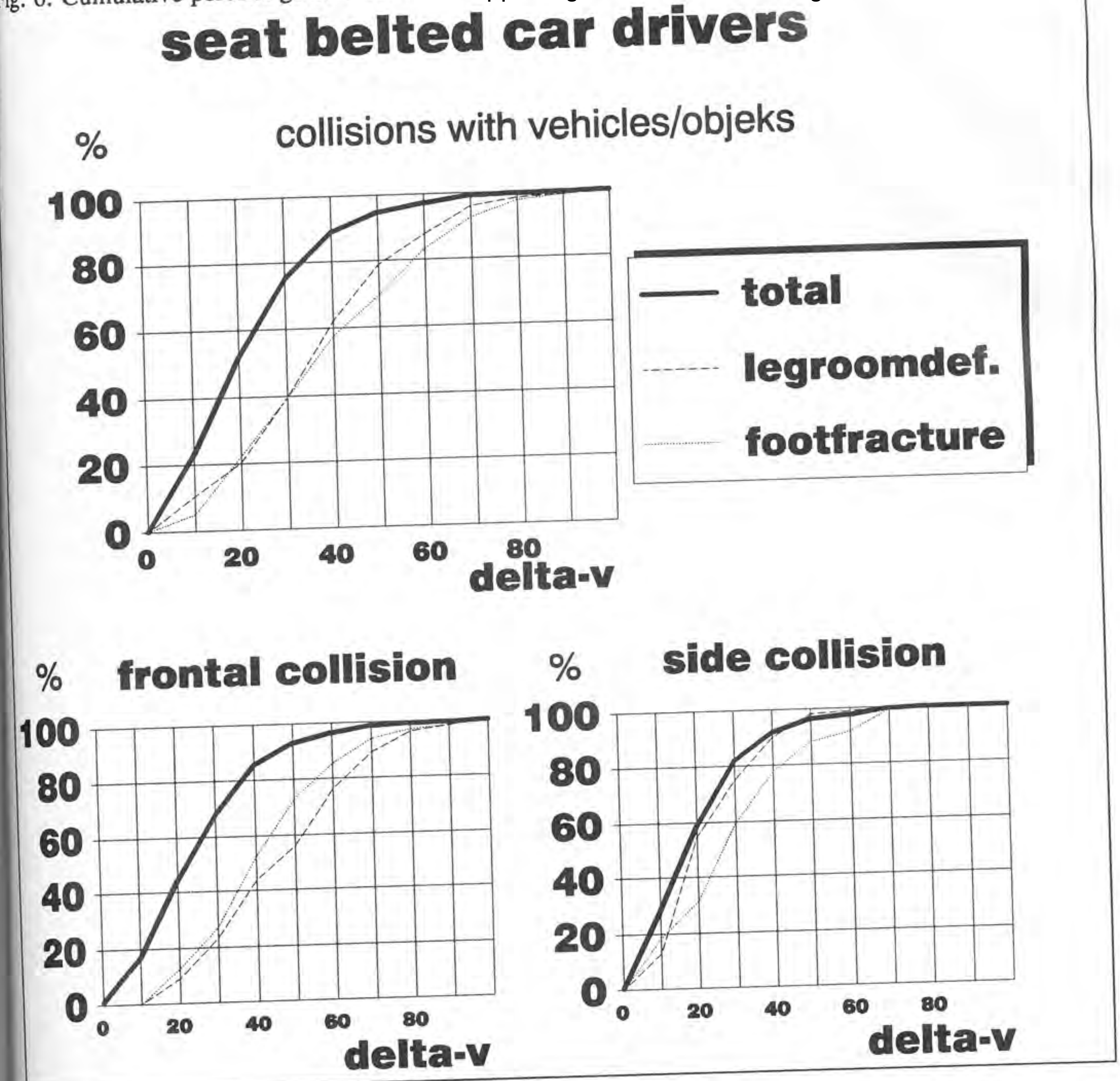


frontal collision side collision

With fractures of the ankle-joint the lateral impact force was observed in almost one third of the cases.

The footroom deformation is a frequent technical attendent as a risk for foot fractures. This means that foot fractures are marked by the accident severity. The speed changing of the collision Delta-v which occurred during the collision phase can be taken as a measurement for the injury severity. For car drivers with foot fractures a higher Delta-v value is on principle observed (fig. 6). Whereas 75% of all belt-protected car drivers are exposed to speed changes of up to 30 km/h in collisions with vehicles and other objects, there are only 40% with foot fractures. As shown in the illustration, the cumulated frequency for footroom deformations is almost analogues to the frequency of foot fractures. Observed were only 40% of footroom deformations in Delta-v values below 30 km/h. In view of the fact that in frontal collisions, due to the long front of a car, footroom deformations occur only at higher Delta-v values than for example in lateral collisions, the dependance of Delta-v on the footroom deformation and on the frequency of foot fractures differs for frontal and lateral collisions (fig. 6). It became evident that in frontal collisions footroom deformations occurred only from Delta-v values of 20 km/h, and foot fractures were observed accordingly, especially metatarsale and ankle-joint fractures, while other regions are observed in more upper levels of Delta-v 30 km/h and more.

Fig. 6: Cumulative percentage of delt



With increasing Delta-v values a different occurrance probability is apparent for variously fractured foot regions. While ankle-joint fractures decrease in relative proportion to the Delta-v values, fractures of the metatarsale visibly increase. This proves that fractures of the ankle-joint appear with low load under a foot movement, when the foot glides down with a side-slip from the brake pedal. Hereby the foot is rotate lateral. Addition to this a sliding of the body produced a load inside the ankle-joint. This mechanism is of considerable importance regards to ankle-joint fractures. With increasing speed change this effect is overlapped by direct force on the middle foot region. In consequence this results in more frequent traumatisation of the metatarsale and phalanx.

4.4 Mechanisms for foot fractures

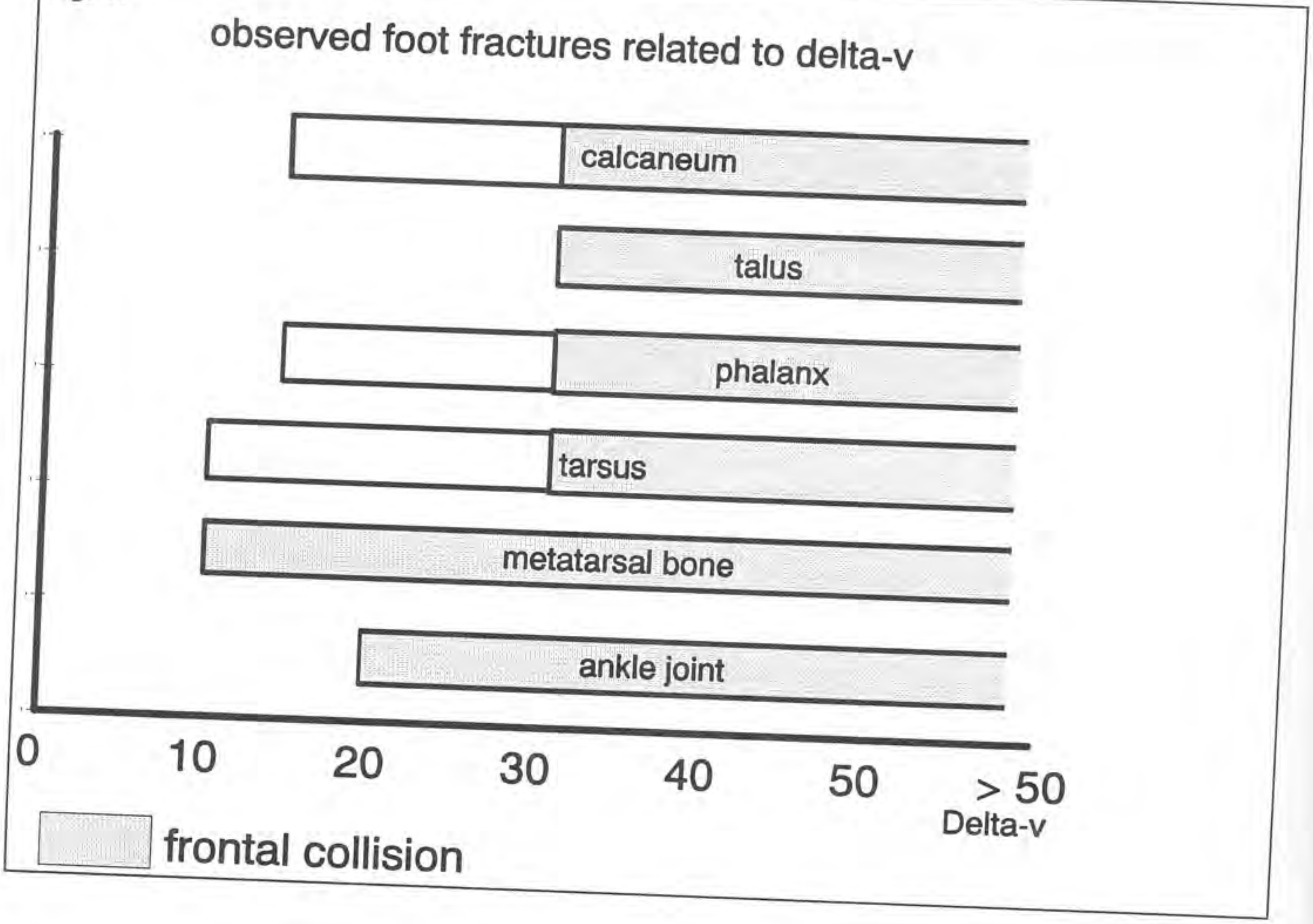
In the analysis 2 different typically injury mechanisms are established:

direct load to the foot / deformation effect

indirect load to the foot / sliding effect.

The transfer of force to the foot, i.e. to the region that is exposed to possible fractures can be regarded as direct pressure. Indirect load, however is responsible for injuries in some distance of the impact. In view of the numerous single bones of the foot, and the multitude of joints, beside axial and bending components, compression and tension are acted on the numerous single foot bones. The ankle joint is a very essential joint which connects the foot with the tibia. Therefore the tibia could brake within this foot load. These combined fractures of foot and tibia/fibula (so called "Weber-fractures") were not observed in seat belt using. So it can be pointed out, that there is no large frontal movement of the body with seat belt and therefore no large bending effect for the ankle joint. Due to the kinematic of the body it provides pressure components which effect the kinetic system of the whole force to the foot. During the collision phase the vehicle occur a deceleration in which occupants continue in their relative movement, due to the mass inertia. This kinematic motion is only partly avoided by belt usage. Legs, head and arms may still move as far as the remaining possibility of movement will permit. This sup-

Fig. 7:



porting movement applies a for[illegible] leg region, and will consequently lead to a lifting-up movement of the foot. The deformation of the footroom will in addition effect a gliding downward movement with slide-side effect from the brake pedal and a following rotation of the bony foot structure. Herewith a turning motion of the ankle joint laterally in opposite direction of the supporting movement occur. Injuries, especially to the joints, can already occur in isolated decelerations, without the additional impact force by the deformation of the footroom. This would explain why in frontal collisions one-fourth of fractures occured without footwell deformations, in the lower Delta-v levels up to 10 km/h exclusively ankle-joint fractures, and occasionally only injuries of the metatarsale were established (fig. 7).

The following kinematic patterns are classified as mechanisms for foot injuries:

jamming compression
plantar flexion
dorsal flexion
pronation
supination
direct deformation load
supporting/body load

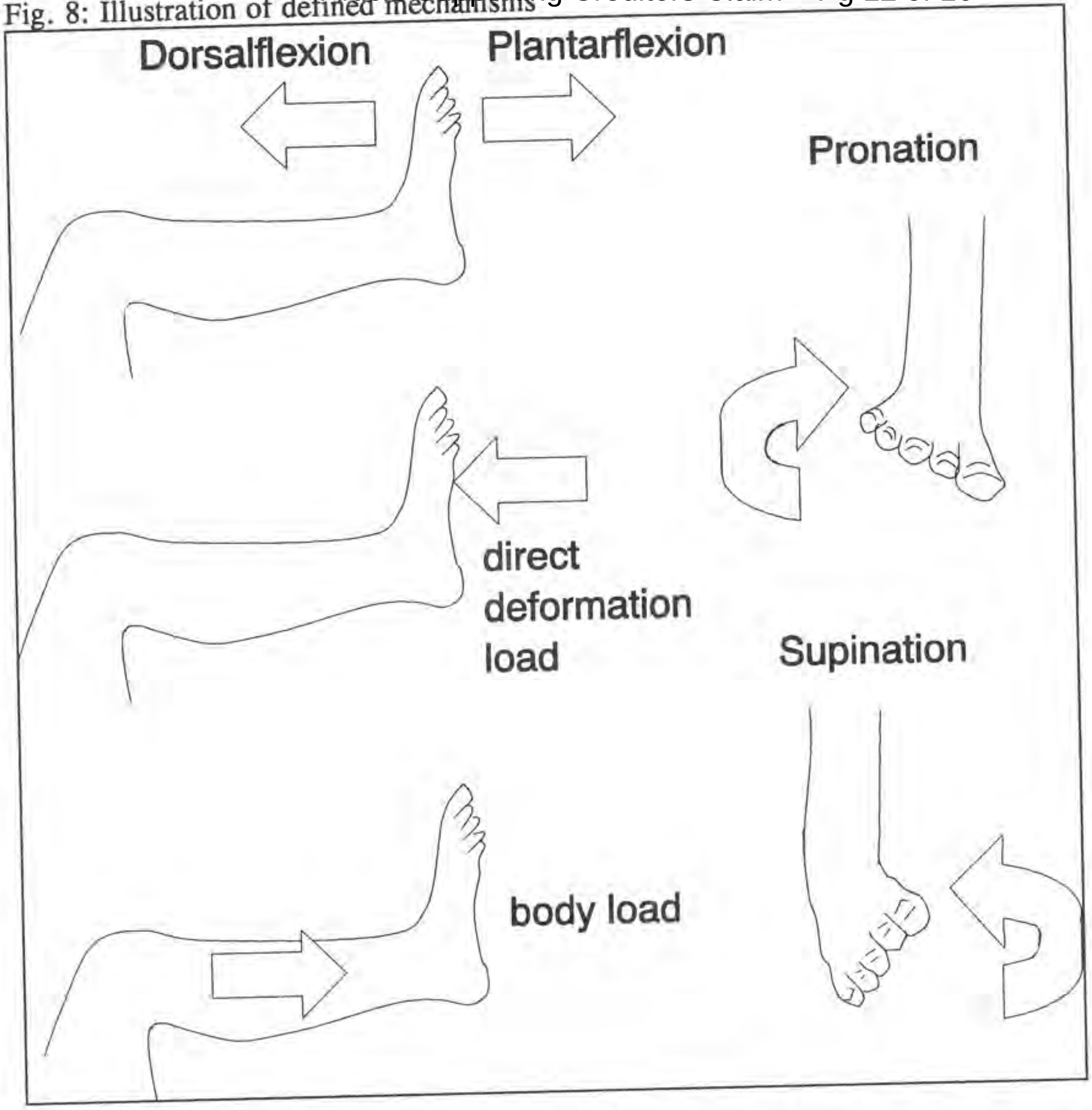
In table 4 the mechanisms for the different fractures are shown. The illustration of the mechanisms is described in figure 8. It is obvious that 10,1% of the mechanism occurred as result of jamming the foot or with compression between deformable structures and also 10.1% occured in direct deformation load. Fractures of the metatarsale were registered with 69.2% as an isolated supporting body load. Fractures of the talus exclusively occur only by supporting, and fractures of the calcaneus by supporting and by the combination of lateral compression, rotation, and body load. Injuries to the ankle-joint were induced very seldom in an isolated supporting mechanism, but more in combination with isolated rotation (45%), impact mechanism and combination with rotation (22.5%) and in addition to body load (22.5%).

Tab. 4:

	total	mechanism						
		compression jammering	plantar flexion	dorsal flexion	pronation	supination	direct impact deformation	supporting body load
total	159	10.1%	0.6%	0.6%	20.1%	17.6%	10.1%	40.9%

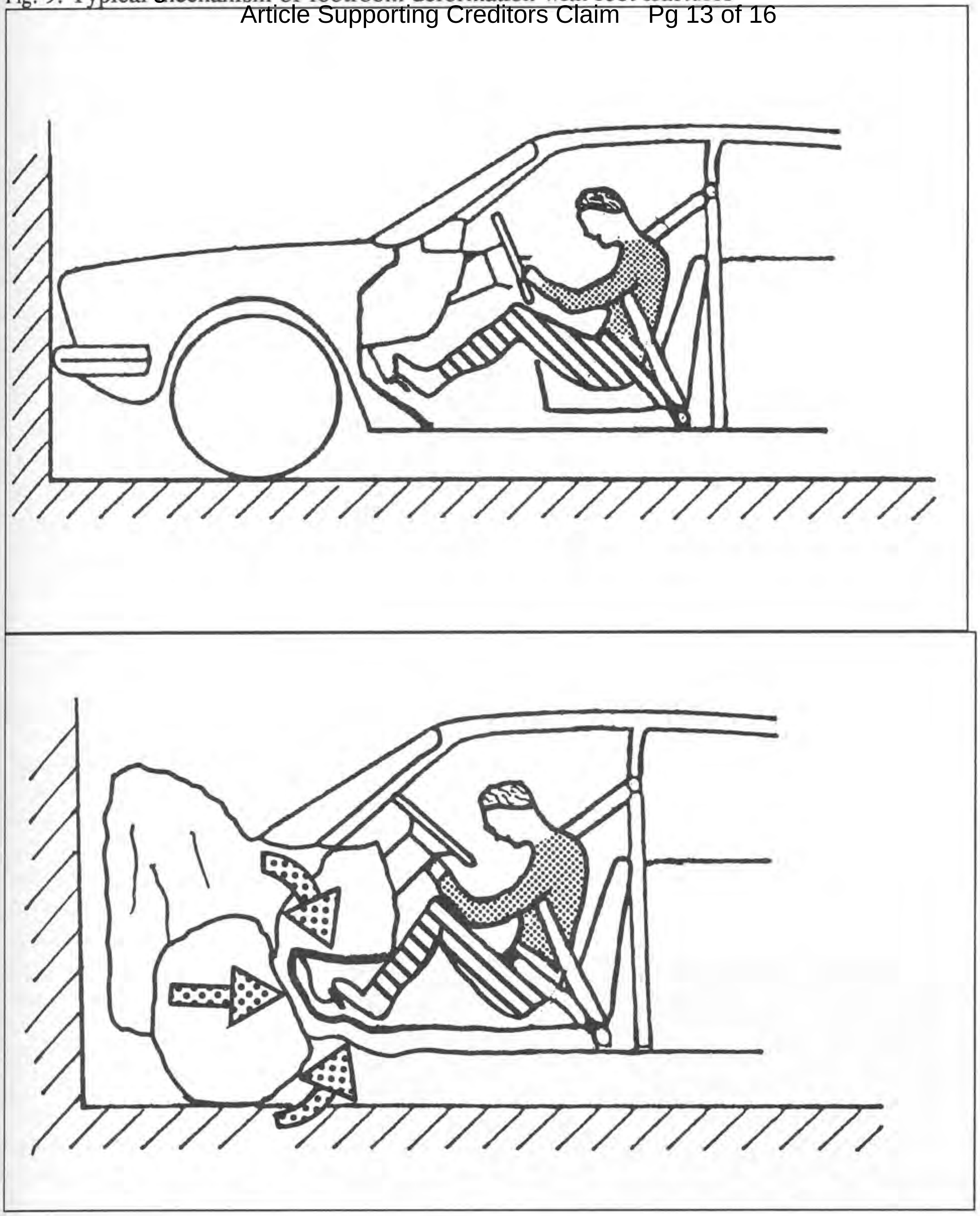
mechanism	total	localisation of foot fracture					
		phalanx	metatarsal	tarsus	talus	calcaneum	ankle joint
total	108	14	39	6	3	6	40
isol. compression	-	-	-	-	-	-	-
isol. rotation	24.1%	7.1%	7.7%	66.7%	-	-	45.0%
isol. impact	3.7%	28.6%	-	-	-	-	-
isol. body load	35.2%	14.3%	69.2%	16.7%	100.0%	83.3%	-
compr. + rotation	8.3%	-	-	-	-	-	22.5%
compr. + impact	0.9%	-	2.6%	-	-	-	-
compr. + body load	2.8%	7.1%	5.1%	-	-	-	-
rotation + impact	3.7%	-	7.7%	-	-	-	2.5%
rotation + body load	12.0%	-	7.7%	16.7%	-	-	22.5%
impact + body load	5.6%	42.9%	-	-	-	-	-
compr. + rot. + body load	1.9%	-	-	-	-	16.7%	2.5%
compr. + rot. + impact	-	-	-	-	-	-	-
compr.+impact+body load	-	-	-	-	-	-	-
rot. + impact + body load	-	-	-	-	-	-	-
all mechanisms	1,9%	-	-	-	-	-	5.0%

Fig. 8: Illustration of defined mechanisms



The single-case analysis did show in almost each case foot injuries when the deformation of the footroom was distinctly marked. Often a deformation of the footroom was shown horizontally in a frontal/lateral direction through the frontal footwell and vertically in caudal direction by the subsiding dashboard. A jamming of a footroom did often occur in lateral direction by the transmission tunnel midsize, with its' stable internal elements such as gearbox and engine block respectively. The characteristics of the footroom deformation is often shown as a sort of 'hollow pyramid', with the feet placed inside. During a deformation event, they compressed from all sides and get even more jammed. In addition to this are subjected to an axial force in direction of the body (fig. 9). Regarding the inflicted injury, it is presumed that the drivers' right foot is placed on the brake pedal, or rather that the left foot beside the pedals is positioned at a lower level behind this. Often oblique impact impulses occur, which in consequence effect an oblique relative motion of the occupants, caused by a rotation movement of the foot. The consequence will either be an outward twisting of the foot, a so-called pronation, or an inward twisting, a so-called supination, in an overlapping up and down movement of the frontal foot region, the plantar or dorsal flexion respectively. The inward

Fig. 9: Typical mechanism of footroom deformation with foot fractures



movement of the pedal and footwell region within the deformation effects gives in this way an intensification of this injury mechanism.

5. Measures for avoidance and reduction of foot fractures

This study clearly demonstrates that foot fractures are induced in direct connection with the deformation of the footroom. They are definitely car-specific injuries which are only caused by the mechanism direct impact load and relative body movement. By this mechanism the feet are loading in leg direction and the body relative movement set against this. Therefore the foot glides off the brake pedal or under the brake pedal causing a rotation of the foot. Then when the footwell deformation is going far the feet are jammed in the deformed footroom and in this way are exposed to bending as well as to compression pressure.

An avoidance of foot fractures appears to be possible when the footroom is not subjected to a deformation. This justifies the demand for a stable passenger compartment in the region of the footroom. First steps in this construction direction can already be seen with some new vehicle models (fig. 10).

The lateral footroom which is already deformed at low force, but especially in lateral collisions, must be included in this stable passenger compartment. The transmission tunnel midsize must also retain its shape. For those foot injuries which occurs without a footroom deformation a low accident severity grade could be established. Therefore a further measure should be a protective construction of the pedals considered, in order to avoid the increase of the axial load for the feet, due to the deformation of the footwell and the consequent shifting in opposite direction to the driver's movement on the one hand. On the other hand to avoid that the pedals' laterally effecting penetrate to the foot, the pedals should not be constructed with a smal edge, but be equipped with a relatively broad side edging. It could be pointed out as a future idea to develop a new pedal modification as electronic sensors in the floor.

An avoidance of footroom deformation is also recommandable, as in todays accident situation, in frontal collisions such deformations occur already at quite low Delta-v values. Figure 11 shows for overlapping degrees of the colliding

Fig. 10: Example of a modern construction of the frame for force transmission to the footwell by Daimler-Benz

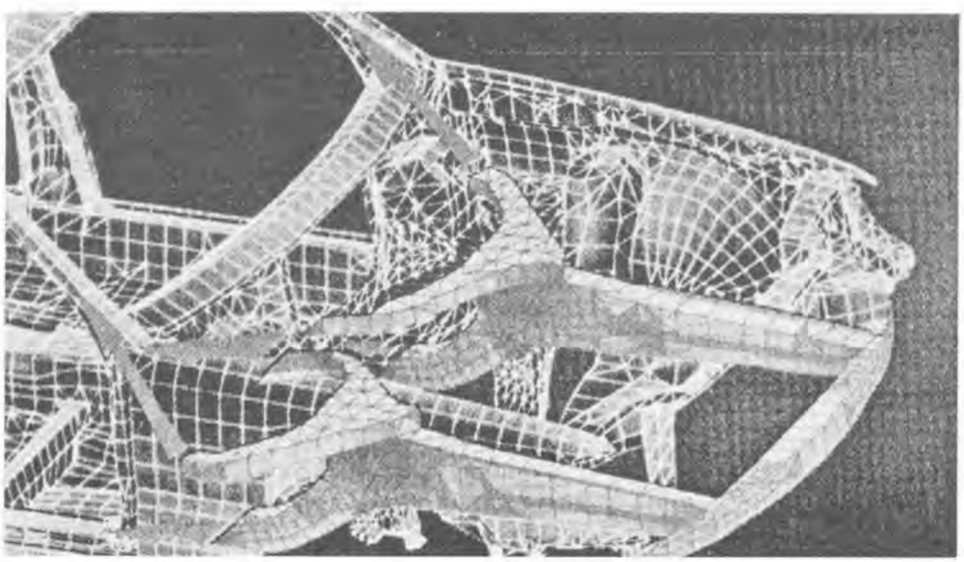
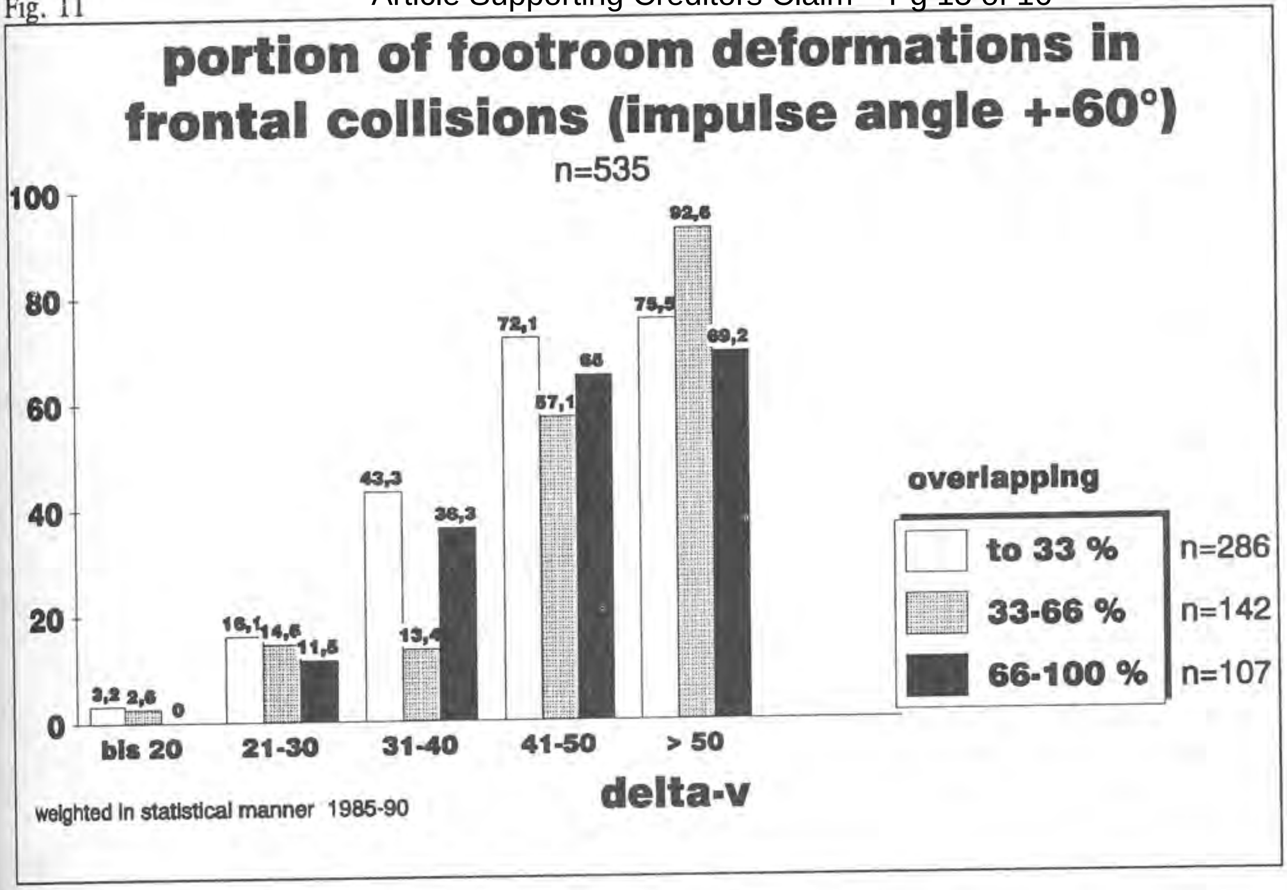


Fig. 11



car front, especially for 1/3 to 2/3 overlapping proportionally high footroom deformations, i.e. up to Delta-v value 50 km/h a 33% overlapping for foot injuries predominates. A test for footroom stability should be included in the framework of a crash-test below one third of overlapping and it must be proposed, that in all test procedures the force will be measured in the foot of the dummy.

6. Discussion

The high frequency of foot injuries in todays traffic situation as claimed in the literature as by Zeidler (3), could not be verified within the framework of the study. Only 8.5% of all injuries sustained by belt-protected car drivers are foot fractures, distortions or luxations respectively.

Despite the fact that foot fractures are with approximately 2% relatively rare for belt-protected drivers, preventive measures are called for. In comparison to other injuries, foot fractures result in a high rate of injury consequences in treatment. According to investigations by the German Professional Trade Association (6), ankle and foot injuries require with 8% the highest rate of stationary treatment, result with 19% in the highest rate of complications, and require with 21% the highest rate of rehabilitation measures. A calcaneus fracture leads most frequently to a reduction in earning capacity (MdE) of 25%, fractured ankle-joints result to a 26.6% reduction of earning capacity. In view of the fact that pension claims can already be made at 20% of working disability, foot fractures must be regarded as a serious type of injury from a traumatologic point of view. This justifies the demand for future vehicle-technique structuring of the footroom in cars:

- stable occupant compartment for the footroom region, including side wall, footwell and transmission tunnel

- protective structuring in geometry of the pedal system.

3/4 of all foot fractures are caused by footroom deformation. Pattimore et al. (7) confirms this in his work and points to the influence of the 'footwell'.

A footroom stability test should therefore be integrated in accordance with crash test conditions. A 1/3 off-set frontal crash test appears to be recommendable for this purpose. The fact that 1/4 of all foot injuries already occur with lesser accident severity and without footroom deformation shows that the limitations for normal kinetic possibilities in the footroom are already exceeded by more supporting or slipping-off movements of the pedals respectively. Technical solutions for this can only be found in a modified construction in geometry of the pedal system.

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